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Abstract

An overlay technique developed for welding irradiated stainless steel may be important for repair or modification of fusion reactor materials. Helium, present due to n,α reactions, is known to cause cracking using conventional welding methods. Stainless steel impregnated with 3 to 220 appm helium by decay of tritium was used to develop a welding process that could be used for repair. The result was a gas metal arc weld overlay technique with low-heat input and low-penetration into the helium-containing material. Extensive metallurgical and mechanical testing of this technique demonstrated substantial reduction of helium embrittlement damage. The overlay technique was applied to irradiated 304 stainless steel containing 10 appm helium. Surface cracking, present in conventional welds made on the same steel at lower helium concentrations, was eliminated. Underbead cracking, although greater than for tritium charged and aged material, was minimal compared to conventional welding methods.

1. Introduction

Cracks were found in the heat-affected zone (HAZ) of repair welds joining patches to the tank wall of a nuclear reactor at the Savannah River Site. Subsequent analysis showed that helium embrittlement caused the cracking adjacent to repair welds in the reactor tank [1]. Helium was present in the reactor vessel wall due to neutron capture by alloy and impurity elements. The mechanism for this embrittlement was attributed to the nucleation, growth and coalescence of helium induced microvoids during the welding process. Scanning electron microscopy and transmission electron microscopy showed the formation of small helium bubbles on grain boundaries in the steel and the presence of dimples on fracture surfaces [2,3]. Similar helium induced structures have been found in type 316 stainless steel containing helium [4,5]. Dimples are believed to result from bubble coalescence that leads to a creep like fracture of the grain boundaries in the weld HAZ. This progression is shown in Fig. 1.

Once helium was identified as the cause of the reduction in weldability, a program was initiated to develop a repair technique that would eliminate or at least minimize helium embrittlement cracking. Type 304 stainless steel charged with helium by tritium decay was used for this program. The application of low-penetration gas metal arc (GMA) weld overlay techniques provided encouraging results by producing a pronounced reduction in cracking compared to the repair welds in the reactor tank [6]. Reduction in helium embrittlement cracking has also been obtained by cold working, precipitate distribution, and by application of compressive stress during welding [7,8].

The overlay technique was developed to minimize heat input to the base material while providing sufficient weld penetration to develop a continuous metallurgical bond between the weld and base metal. The technique included a weld weave to produce a one inch wide weld overlay that is approximately 0.9 mm thick using 308 filler wire. Weld penetration into the base metal was approximately 0.08 mm. This minimal penetration reduced the size of the high temperature and high stress regions in the substrate material. Metal transfer to the overlay was by the short-circuit mode and high speed cross seam mechanical oscillation of the arc.

The overlay welds were quantitatively analyzed using tensile and bend tests for measurement of weld mechanical strength [9], and by optical metallographic characterization and SEM fractography of weld damage caused by helium embrittlement [2,3,9].

Results from the extensive testing performed on tritium charged and aged material have now been compared with damage caused by overlay welds on

304 stainless steel irradiated to 5 and 10 appm helium. This paper provides a summary of the results on material containing helium from tritium decay, reports results for overlay welds on irradiated material, and makes a comparison of embrittlement experienced from the two implantation methods.

2. Test program on tritium charged and aged stainless steel

The effectiveness of this shallow penetration overlay process on helium bearing steel was demonstrated by welding Type 304 stainless steel plates that had been charged with tritium at the Sandia National Laboratory. Helium was produced in the plates by tritium decay, and the tritium was then removed by outgassing. Plates contained preselected helium contents between 3 to 220 appm (atomic parts per million). The helium content, which was confirmed by chemical analysis, was controlled by the tritium charging conditions (temperature, pressure and time) and the time for tritium decay. Overlay welds, along with gas tungsten arc (GTA) and gas metal arc (GMA) stringer beads for comparison, were made across the helium-containing plates.

2.1 Crack distributions

External surfaces of the welds were visually examined and penetrant tested for toe cracks (large surface cracks in the HAZ around the edge of a weld bead) and porosity (gas bubbles in the weld metal that may be open to the surface or may be trapped within the weld metal below the surface). Both toe cracks and porosity result from helium in the base metal. Toe cracks form from the agglomeration of small (2-3 nm diameter) helium bubbles on grain boundaries and the weld induced coalescence of those bubbles to form an intergranular crack. Porosity results simply from the macroscopic release of helium from the base metal during welding.

Surface examination of the welded plates revealed no toe cracks or porosity associated with the overlay welds. However, welds made by the conventional GTA or GMA processes had both toe cracks and extensive surface porosity. Toe cracks for the highest heat input conventional welds were typical of those seen during repair of the reactor tank. Metallographic examination of test welds in tritium charged and aged stainless confirmed the lack of toe cracking in overlay welds compared to conventional welds (Fig. 2).

Light microscopy of the overlay welds confirmed that surface cracks were eliminated, and quantitative analysis of underbead cracking showed a substantial reduction compared to conventional welding methods. The helium induced cracks were totally intergranular. This was true for both the surface toe cracks and the underbead cracks. The underbead cracks were located in the HAZ of welds but do not generally intersect the material surface. Typically underbead cracks are smaller than toe cracks and lie in a narrow, 2 mm band adjacent to weld metal. Occasionally, underbead cracks extend for a very short distance (0.05 mm) into weld metal.

Among the variables examined to determine the extent of cracking were base metal helium concentration, weld penetration, effect of multiple layer overlays, and type of weld. The extent of cracking increases with helium concentration. More important for choosing a weld repair procedure for irradiated material is the effect of the type of weld. The overlay technique reduces underbead cracking compared to GTA stringer beads at equivalent weld heat inputs. This result, along with the elimination of toe cracks, is strong evidence for the promising use of the overlay technique for welding on helium-bearing material.

An additional practical advantage of use of overlays is the ability to build up multiple layers should a thick overlay be needed. This study has shown that the effect on underbead cracking of adding a second layer is negligible.

2.2. Mechanical tests

Two tests methods were used to evaluate the mechanical integrity of the weld overlay process on helium-containing 304 stainless steel. Tensile testing of the bond between the overlay and the base plate was used to evaluate the strength and ductility of the HAZ and of the interface between the overlay and the base plate. Bend testing was used to determine the effect of stress on existing helium embrittlement cracks.

Tensile tests of the overlay welds showed that strength is not compromised up to about 35 appm helium. Values of the ultimate tensile strength, yield strength, and reduction of area were obtained. The change in mechanical properties due to helium embrittlement was clearly reflected by a pronounced decrease in the reduction of area at about 35 appm helium. Coincident with this loss of ductility was a change in the appearance of the fracture surfaces. Scanning electron microscope analysis of the tensile samples showed that the failure mode changed from ductile dimple rupture in the base metal at low helium concentrations to brittle intergranular fracture of the underbead heat-affected zone at high helium concentrations.

Bend tests showed that helium embrittlement cracks do not propagate beyond the weld HAZ even under severe stress. Specimens were examined with a scanning electron microscope in the areas of uniform strain near the center of each specimen. At all helium levels cracking was intergranular and was restricted to the HAZ. Although the width of the cracks increased during bending, their length was almost constant demonstrating the localized nature of the helium embrittlement damage.

3. Test program on irradiated stainless steel

To test the applicability of the overlay technique to irradiated material, welds were made on a six inch diameter disc core drilled from the wall of a Savannah River reactor. At the reactor tank wall position from which the disc was removed, the radiation fluences were 2.6 x 10^{21} n/cm^2 thermal and 7.6x10^{20} n/cm^2 fast. This irradiation produced measured helium contents of 10.4 appm on the inside surface and 5.0 appm on the outside surface of the disc. The disc is 1.3 cm thick 304 stainless steel with a slight curvature due to the 4.9 m diameter of the reactor tank.

An overlay weld approximately 7.6 cm long and 2.6 cm wide was made on each side of the disc (Fig. 3). Welding was performed remotely in a manipulator cell facility.

No surface cracks were present as determined by dye penetrant testing and metallographic examination of the overlay welds (Fig. 4A). The overlay method therefore eliminates toe cracks, present in conventional welds made in irradiated material at much lower helium concentrations. Conventional welds made previously in irradiated material resulted in deep surface cracks and underbead cracks (Fig. 4B) in the heat-affected zone of welds. Comparison of the photographs in Fig. 4 shows clearly the reduction in cracking achieved using the overlay method, particularly considering that the overlay was placed on a surface with three times the helium content compared to the material in which the conventional weld was made. Such cracks caused leaks in the patch welded in a Savannah River reactor in 1986 and resulted in permanent shutdown of that reactor [1].

Analysis of the cracks was completed by counting the number of cracks and the crack length in several sections of each overlay weld. Measurements showed approximately twice the amount of cracking beneath the overlay weld made on the material with 10.4 appm helium as on the material containing 5.0 appm helium. An area with the greatest concentration of cracks observed for the overlay welds is shown in Fig. 5. Cracks were observed in the weld metal at several locations, generally extending from underbead heat-affected zone cracks as in Fig. 5.

This analysis demonstrates that the overlay technique is applicable to 304 stainless steel impregnated with helium by irradiation as well as by tritium decay. Surface cracking is eliminated and underbead cracking, although greater than for tritium charged and aged material, is minimal compared to conventional welding methods.

4. Comparison of implantation by tritium decay and irradiation

The effect of helium on the weldability of stainless steel is expected to differ depending upon implantation technique for a number of reasons. Primary among these is the anticipated difference in distribution of the helium in the microstructure. Helium from transmutation of boron in the stainless steel matrix is expected to be in the grain boundaries due to the location of boron as an impurity element. On the other hand, helium from transmutation of nickel is expected to be spread throughout the matrix. Helium from diffusion of tritium is also expected to be at a combination of grain boundary and matrix locations. The overall effect of these differences was unknown until the present study.

Although cracking was minor in overlays made on the irradiated material, it is considerably higher than that experienced for the tritium charged and aged material at the same helium concentrations. This result holds for both conventional welds, where measured crack lengths were 31 times greater in irradiated material compared to tritium charged and aged material, and for overlay welds, where measured cracks lengths were 28 times greater. Results are shown in Fig. 6 for a helium concentration of 10 appm. Results are based on measurements of cracking at 10 appm and are given additional credence by projections from welds at a series of helium concentrations. Measurements of cracking on tritium charged and aged material are presented in more detail in reference [9]. Measurements for overlays on irradiated material are from the present work and measurements for conventional welds on irradiated material are from unpublished work at helium concentrations up to 12 appm.

5. Conclusions

Welding of 304 stainless steel containing helium causes cracking in the weld heat-affected zone. Cracking is due to agglomeration of helium in grain boundaries combined with the high temperatures and stresses encountered during welding. Techniques which reduce the thermal and mechanical impact in the weld area are being developed to minimize cracking.

A low-penetration overlay technique has been developed for welding helium-containing materials. Elimination of large surface cracks and reduction of underbead cracking has been demonstrated for the technique on material charged with helium from tritium decay and on irradiated material. This technique is expected to be a practical method for repair or modification of fusion reactor components.

Specific comparisons between helium implantation by tritium decay and by irradiation are:

- Helium embrittlement cracking is significantly higher for irradiated material than for tritium charged and aged material.
- The overlay welding method eliminates surface toe cracking at the helium

concentrations investigated (up to 10.4 appm in irradiated material and up to 220 appm in tritium charged and aged material). Toe cracking occurs in the heat-affected zone of conventional welds in both materials.

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Progression from Helium Bubble Formation to Grain Boundary Cracking During Welding

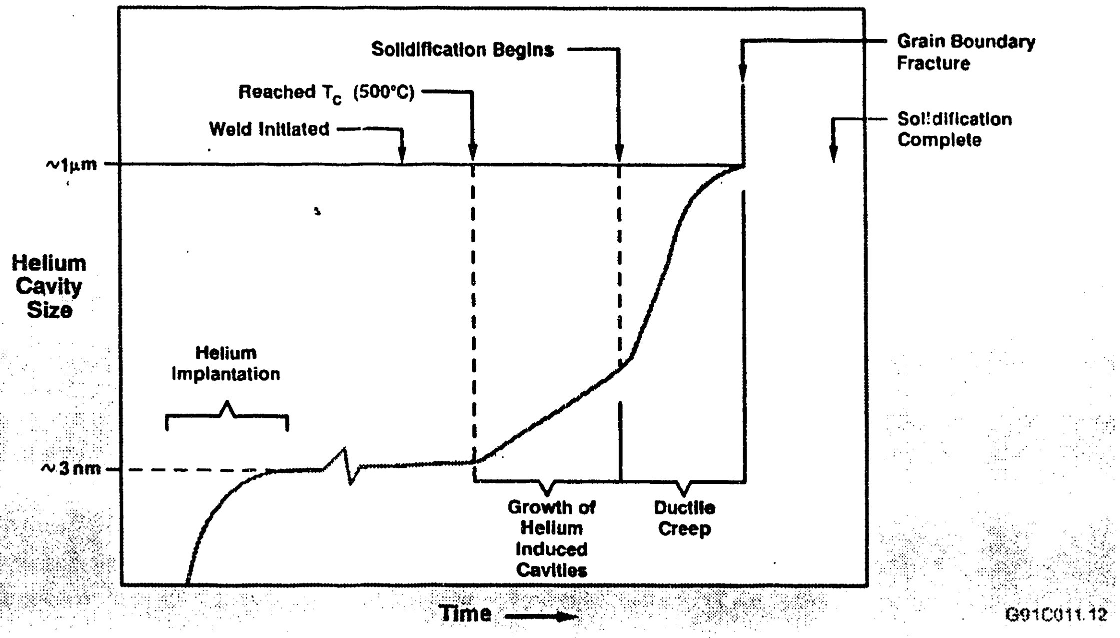
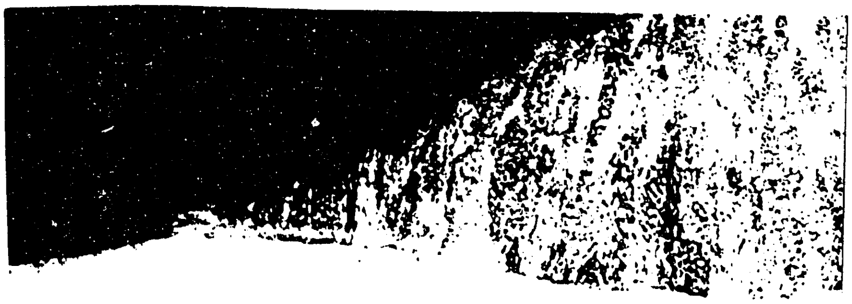


Figure 1. Progression from helium bubble formation to grain boundary cracking during welding.



A. Low penetration gas metal arc overlay weld. 40X.

B. Toe cracks in conventional gas tungsten arc weld. 12X

Figure 2. Comparison of cracking in welds made on tritium charged and aged 304 stainless steel. Note the absence of cracking in the overlay.

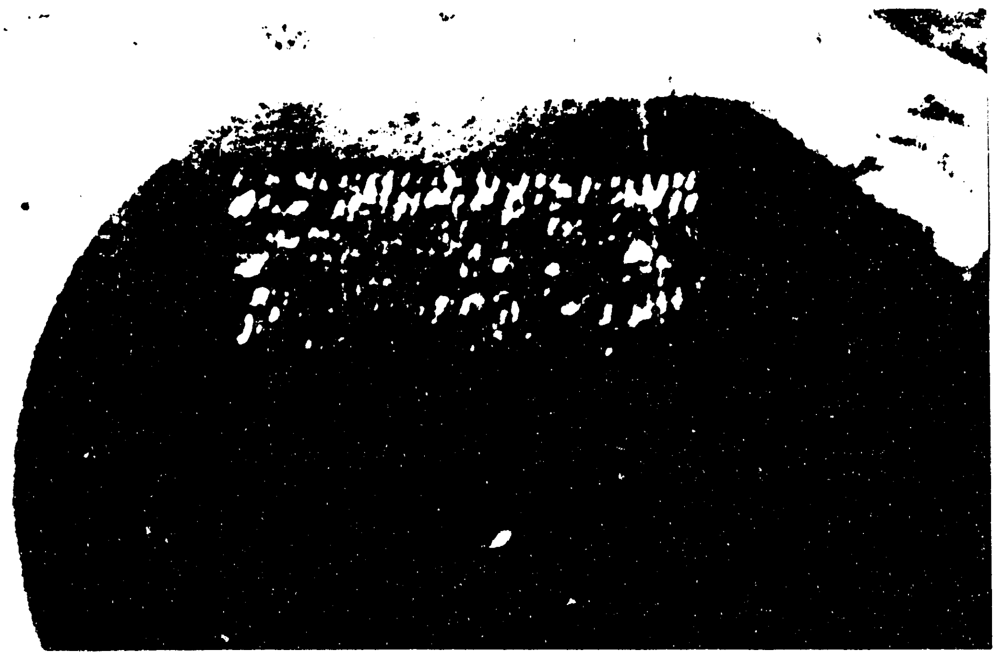
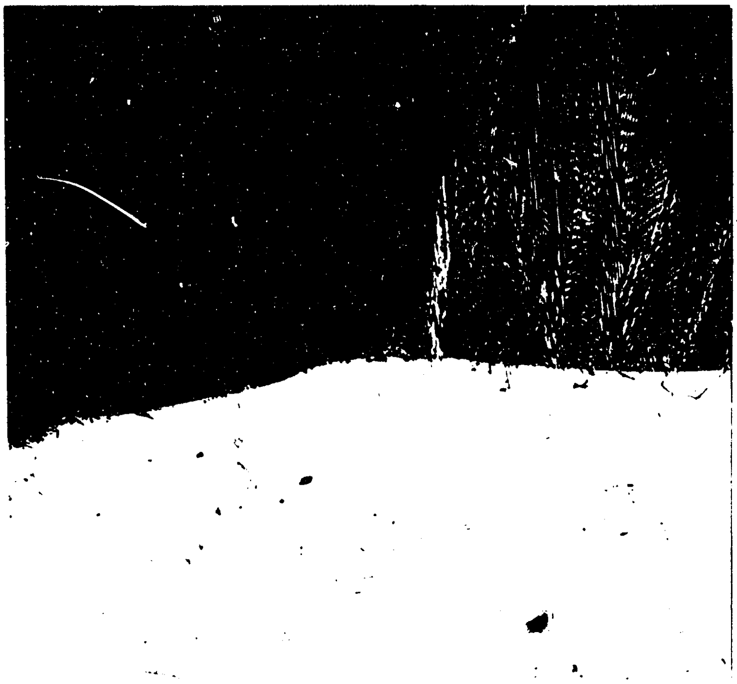
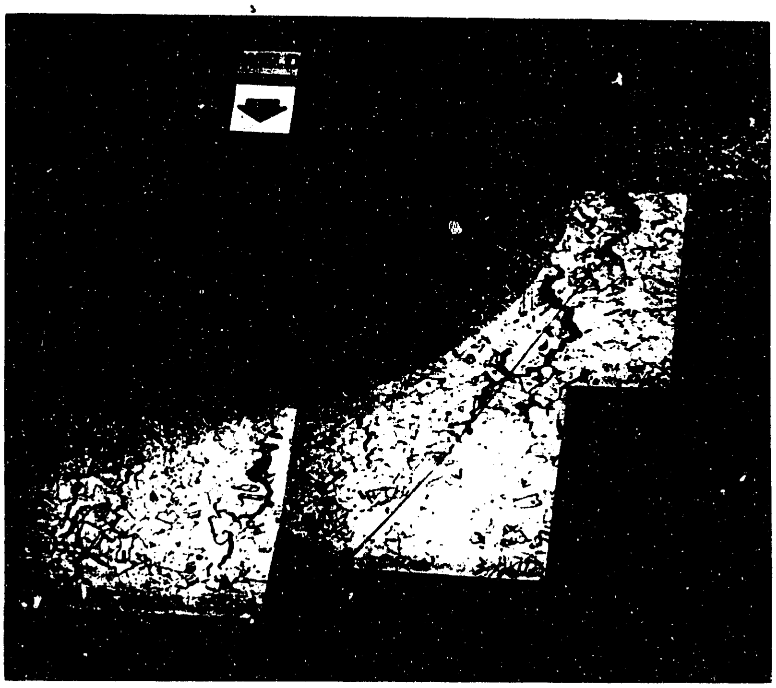


Figure 3. Overlay weld made on irradiated 304 stainless steel containing 5.0 appm helium. 0.9X



A. Low penetration overlay weld, edge location,10.4 appm helium. 50X.



B. Conventional gas metal arc weld, 1.5 appm helium. 20X.

Figure 4. Metallographic sections of welds made in irradiated 304 stainless steel. Note the absence of cracking in the overlay weld.

Figure 5. Metallographic section in location with large underbead cracks in irradiated material with 10.4 appm helium. Dark area on top is weld metal and light area in lower half is base metal including the heat-affected zone. Note that some cracks extend from the heat-affected zone into the weld metal. 50X.

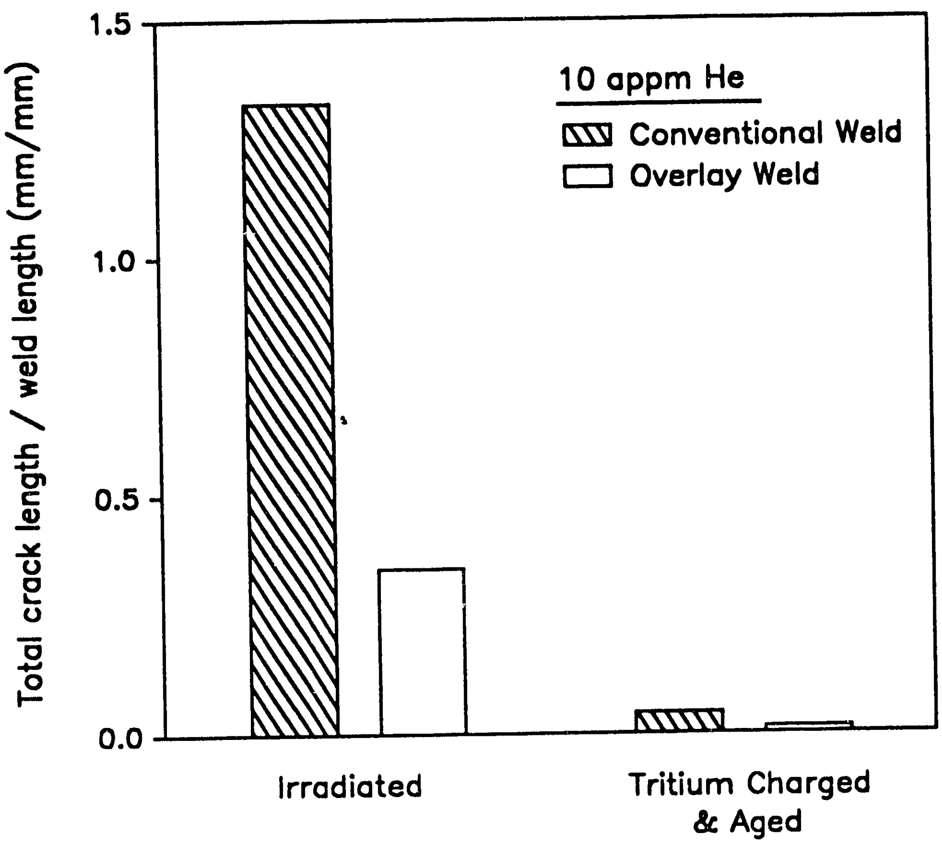


Figure 6. Bar chart summarizing quantitative analysis of underbead damage due to helium embrittlement cracking of 304 stainless steel charged to 10 appm helium. More cracking was measured for conventional welds than overlay welds. More cracking was measured for welds in irradiated material than in tritium charged and aged material.

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